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(1) Selective "blindness" to approaching or receding motion in depth exists and seems to be not uncommon in normally-sighted individuals. Of 16 subjects, 8 had visual field defects for either approaching or receding motion. Of 21 subjects, only 6 had full symmetric fields for oscillatory motion in depth. Visual sensitivity to sideways motion was normal in stereomotion-blind areas. The possible relevance to aviation is pointed out. (2) A perfectly camouflaged bar within a random dot pattern was rendered visible by moving dots within the bar and outside the bar with equal and opposite velocities (motion parallax). The bar's orientation could be judged with equal precision (0.5 deg) to that of an uncamouflaged dotted bar made visible by brightness contrast providing that dot speed and contrast were high. But when contrast was reduced, discrimination collapsed for the camouflaged bar earlier than for the uncamouflaged bar. This suggests that helicopter pilots may be at risk of making visual judgment errors in nap-of-the-earth flight where some objects and ground features are seen by motion alone. (3) Data collection is complete on measuring shape

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19. Abstract (continued)

discrimination of camouflaged objects. (4) ~~Nonlinear systems~~ analysis: We have developed a new mathematical approach to testing multi-neuron models in which individual neurons are modelled as rectifiers. (5) We have developed a nondestructive zoom-FFT technique that allows spectra of EEG and other time series to be computed with the theoretical resolution allowed by the Heisenberg-Gabor relation, e.g. 50,000 lines DC-100 Hz at a resolution of 0.002 Hz from a 500-sec recording. (6) By using a 2-sinewave nonlinear analysis approach in recording human evoked potentials we have found that both vertically-tuned and horizontally-tuned responses have a bandwidth of about 12 deg, and that there is a strong nonlinear interaction between horizontal and vertical. (7) A magnetically shielded room has been installed at York University, and installation of a 7-channel neuromagnetometer will be completed in December. (8) A book, Human Brain Electrophysiology, written by the P.I. will be published mid-December 1988. (9) Two books edited by the P.I., one on "Binocular Vision" and one on "Spatial Form Vision" are in preparation.

> Keywords: Binocular vision;

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2a. Objectives: Psychophysical

(1) Further define the roles of the channeling hypothesis in: (a) identifying specific visual processes; (b) understanding visual performance; (c) specifying visual parameters likely to be important in eye-hand coordination, especially in aviation and flight simulator visual displays.

(2) *Camouflage and the visual processing of objects defined by motion alone.* For camouflaged objects that are invisible except when there is motion parallax between the object and background, measure spatial discriminations, and in particular the hyperacuities, orientation discrimination, spatial frequency discrimination, and line interval discrimination. Compare these data with the corresponding hyperacuities for objects defined by luminance contrast, and find whether both sets of data can be explained by an opponent or line-element model of spatial form discrimination proposed previously.[1-5]

2a. Objectives: Neuromagnetism and electrophysiology

(1) Link the channeling modes of human psychophysics with the activation of different sensory projection areas in human cortex.

(2) Identify evoked activity in different visual, auditory or somatosensory projections in human cortex and elucidate the differences between the type of processing occurring in the different areas. Link these data with the known functional neuroanatomy of macaque monkey brain and with human psychophysics.

(3) Elucidate the temporal sequence of activation of different cortical areas evoked by different kinds of complex visual auditory and somatosensory stimuli. These data will complement scanning data (e.g. regional cerebral blood flow, PET) that lack the temporal resolution offered by neuromagnetic recording.

(4) Elucidate relationships between simultaneous activities of different cortical areas within a single modality (visual, auditory or somatosensory).

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(5) Identify the cortical sites of interactions between responses to stimuli of different modalities, and compare these sites with the known poly-sensory cortical areas in nonhuman primates.

(6) By combining neuromagnetic and evoked potential recording, exploit their complementary natures to improve the localization of generator sites.

(7) Locate the brain sites of abnormalities in patients with known specific sensory defects including selective orientation-tuned visual loss for intermediate spatial frequencies, stereomotion "blindness", specific defects of shape recognition, selective deafness to frequency changes.

2b. Status of the Research Effort: Psychophysical

(1) *Specific "blindness" to oscillatory and unidirectional motion in depth.*

As an object moves towards the head its two retinal images move in opposite directions. This binocular cue alone can generate a strong impression of motion in depth (stereomotion). We have previously published visual fields for oscillatory motion in depth and found that normally-sighted subjects have areas of specific blindness to stereomotion.[6,7] Of the six subjects reported, five showed stereomotion field defects. We have now extended the data base to a further 21 normal subjects, and confirm that stereomotion field defects are common. Only 6/21 subjects had full symmetrical fields.

We now report the existence of selective blindness to unidirectional motio. in depth. Of 16 subjects whose visual fields were tested for approaching and for receding motion in depth, only 5 had similar fields for approaching and receding motion.

Table 1 summarizes the data. Figure 1 illustrates stereomotion fields that were full and symmetrical. Figure 2 shows fields for a subject with field defects and areas that were "blind" to motion in one direction.

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Table 1. Summary of results for 21 normally-sighted subjects. Key: D – different fields. S – similar fields. U – unclassified. U(PR) – unclassified with poor reproducibility.

	SINEWAVE FIELDS		RAMP FIELDS			
			FAR / NEAR		TOWARDS / AWAY	
SUBJECT	LARGE	FAR / NEAR	TOWARDS	AWAY	NEAR	FAR
1	-	D	U	U(PR)	U(PR)	S
2	-	D	D	D	D	U
3	-	D	U	S	D	U
4	-	D	S	S	S	S
5	-	D	S	D	S	D
6	-	D	S	D	D	S
7	-	D	D	D	S	U
8	-	S	U(PR)	U(PR)	U(PR)	U(PR)
9	-	S	S	S	S	S
10	X	S	S	S	S	S
11	X	U	U	S	D	S
12	-	U	D	S	D	S
13	-	S	S	S	S	S
14	-	S	S	U	U	S
15	X	S	S	S	S	S
16	X	S	-	-	-	-
17	-	S	-	-	-	-
18	X	S	-	-	-	-
19	-	S	-	-	-	-
20	X	S	-	-	-	-
21	-	D	U(PR)	D	U(PR)	U

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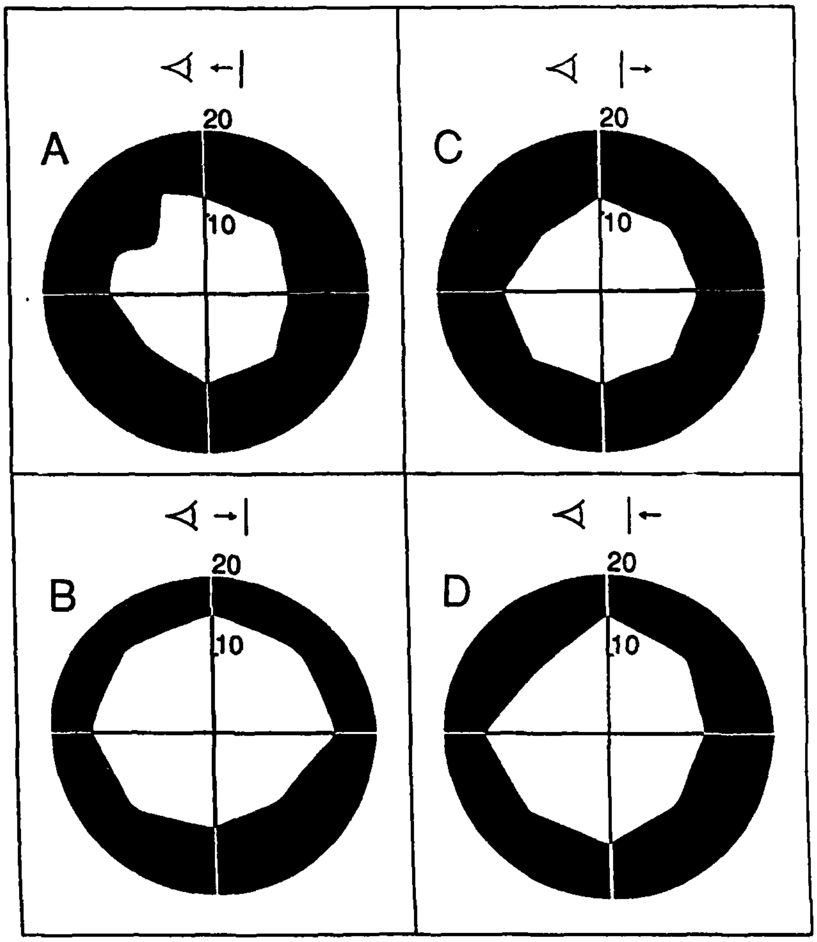

Figure 1. Visual fields for unidirectional depth perception. A subject with similar large fields for approaching and receding motion.

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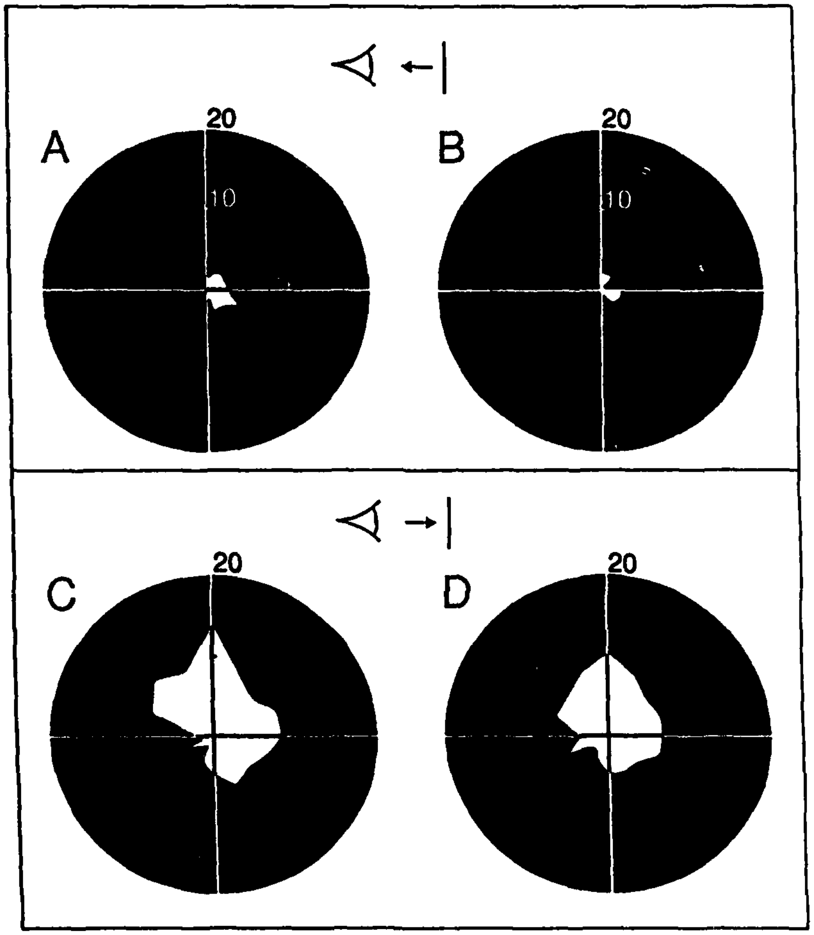

Figure 2. Large visual field defect for unidirectional depth perception. A,B; near disparities, approaching motion. C,D; near disparities, receding motion.

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Because sensitivity to monocularly-viewed motion showed no abnormalities corresponding to the binocular stereomotion "blind spots" we conclude that the stereomotion field defects were chiefly due to the *cortical* processing of motion. We also conclude that unidirectional motion defects are caused by a loss of sensitivity to unidirectional motion in depth rather than to abnormal interactions between mechanisms for approaching and receding motion. These findings provide further evidence that the human visual pathway contains different binocular mechanisms for position in depth and for motion in depth, and that stereomotion blindness is due to a selective loss of the motion mechanism.

These findings raise the possibility that stereomotion "blind spots" are not uncommon in pilots, and that the trajectory of an oncoming aircraft might be misjudged if it passed through a stereomotion "blind spot".

A report on the results to date has been accepted by *Vision Research*.(8)

(2) *Orientation discrimination for camouflaged objects defined by motion alone and for objects defined by luminance contrast*

A pseudo-random pattern of bright dots subtending 2.2 x 2.2 deg was generated by hardware of our own design. Frame rate was 200 Hz. Dots subtended 2.0 min arc, mean separation was about 6 min arc and there were approximately 1000 dots. The dots were optically superimposed on a circular uniformly-illuminated area of diameter 3.7 deg. A 1.5 x 0.22 deg bar-shaped area within the dot pattern was rendered visible by moving dots inside this area leftwards and outside this area rightwards at constant velocity. When the dots were stationary the bar was perfectly camouflaged. Dot contrast was varied by neutral density filters. Orientation discrimination was measured by temporal two-alternative forced choice. The dot pattern was presented for 1.0 sec, and contained a motion-defined vertical bar. Then there was an interval of 0.5 sec followed by a second presentation of 1.0 sec with the bar inclined at some angle θ. There were 10

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possible values of θ. Bar location was randomly jittered and a fresh random dot pattern was generated for each presentation. The subject pressed one of two buttons depending on whether θ was clockwise or anticlockwise of vertical. Orientation discrimination threshold was calculated by Probit analysis.

In separate experiments orientation discrimination was measured for a non-camouflaged bar that was created by omitting the dots in the area surrounding the bar. This target is illustrated in Figure 3.

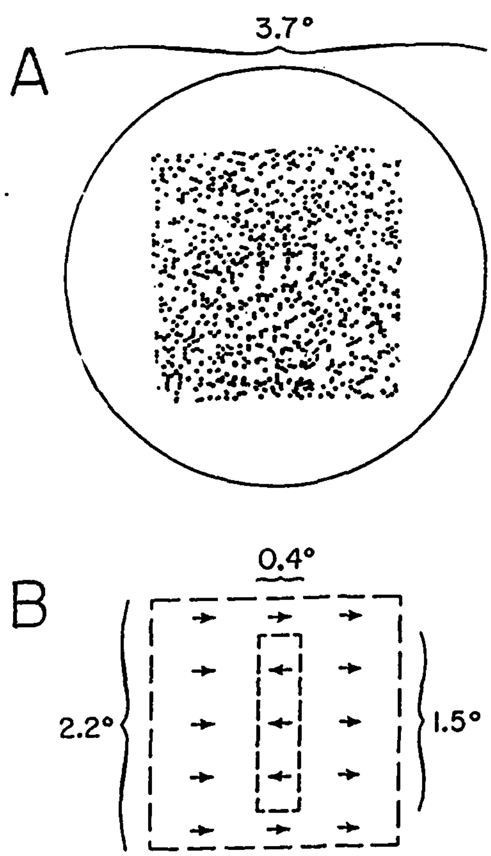

Figure 3. A – random dot pattern containing a perfectly camouflaged bar. B – the bar was revealed by moving dots within the bar and outside the bar in opposite directions.

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The rationale of this experiment is that, for the camouflaged bar, figure ground segregation was achieved by motion alone but the non-camouflaged bar was rendered visible by luminance contrast. Dot density and velocity within the bar were identical in the two cases.

Figures 4 and 5 show that, for high dot velocities and contrasts, orientation discrimination is similar for motion-defined and contrast-defined bars. Furthermore, at about 0.4 deg, discrimination compares favourably with the most acute values reported in the literature for conventional bright solid bars or lines. This finding may relate to our previous finding that vernier acuity for a camouflaged dotted bar can be as high as for a non-camouflaged dotted bar (see Final Report dated 1987/09/14 and Reference #9).

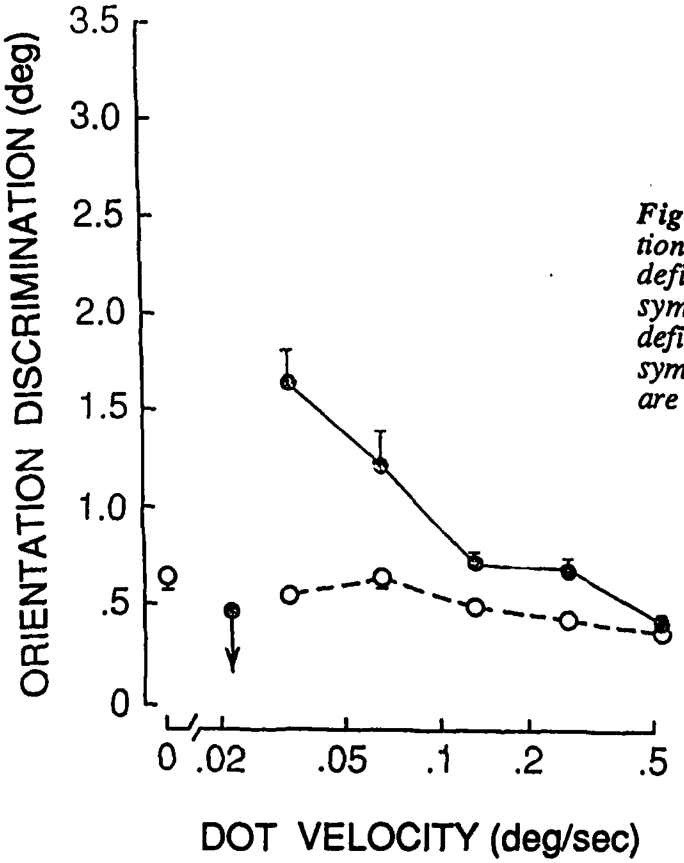

Figure 4. Orientation discrimination versus dot speed for a dotted bar defined by relative motion (open symbols) and for the same bar defined by luminance contrast (filled symbols). Bar detection thresholds are arrowed.

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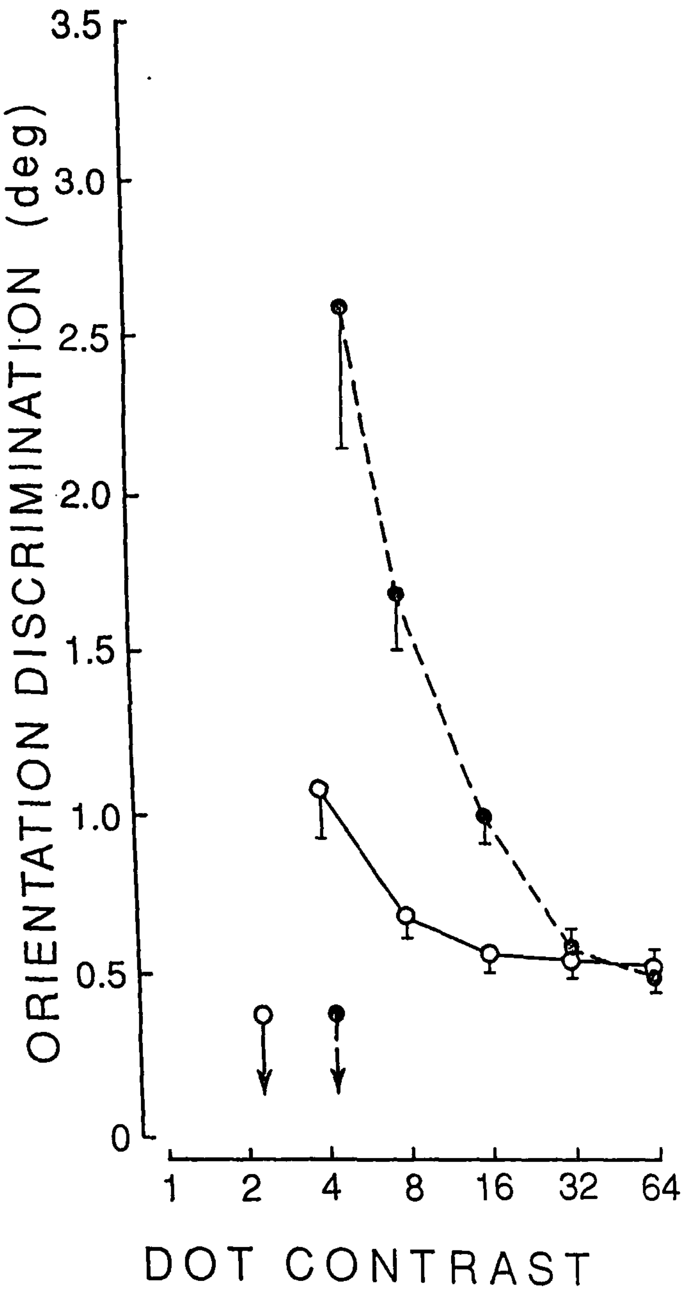

Figure 5. Orientation discrimination versus dot contrast. Other details as in Figure 4.

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But Figure 5 also shows that, as contrast is reduced, discrimination collapses earlier for the motion-defined bar than for the contrast-defined bar. In particular, there is a contrast range of about 4:1 over which discrimination has collapsed for the motion-defined bar but is still good for the contrast-defined bar. *The significance of this is that it suggests that in nap of the earth helicopter flight, where some ground features are visible by motion alone while others are visible by contrast, a pilot's visual judgements might fail for motion-visible objects but not for contrast-visible objects even though the motion-visible objects are still clearly visible.*

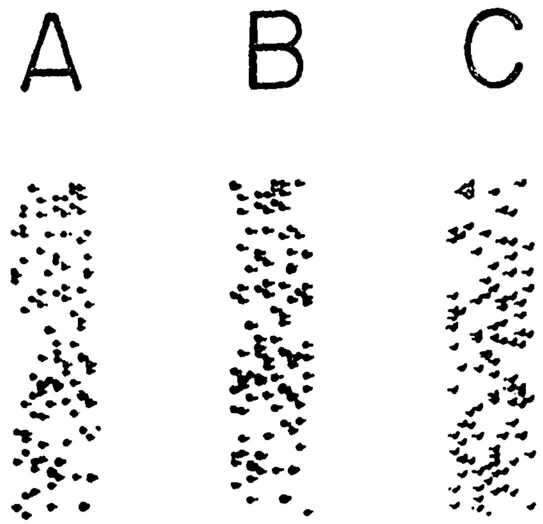

Figure 6. A–C are three snapshots of the dotted bar taken during a 1.0 sec presentation. The dots surrounding the bar were switched off.

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Turning back to Figure 4, we now consider the effect of dot velocity on discrimination for the camouflaged motion-visible bar. It is, in principle, possible that dot motion might improve discrimination by reducing errors due to spatial sampling by dots. Figure 6 illustrates this point. Because of the coarse spatial sampling provided by the sparse dots, the orientation of the bar's edge is poorly defined in each photograph. But, in principle, orientation could be more precisely defined by taking all three "snapshots" into account. However, Figure 4 shows that this effect did not occur for the contrast defined bar (filled symbols). We can therefore assume that the effect of velocity on discrimination for the camouflaged bar (open symbols) was due to velocity sensitivity of motion-sensitive mechanisms rather than to sampling errors.

A preliminary report of this study has been submitted to *Vision Research*.(10)

(3) *Shape discrimination for camouflaged objects defined by motion alone and for objects defined by luminance contrast*

We have used a similar technique to that described in #2 above to generate a camouflaged rectangular shape that is visible by motion alone. The percentage difference between vertical and horizontal sides has 10 possible values, and these are presented randomly. The subject's task is to press one of two buttons depending on whether the longer sides are vertical or horizontal. To ensure that both dimensions must be compared, different areas of rectangle are interleaved randomly. To ensure that the distance of any edge from the boundary of the display provides no cue to shape, the rectangle's location is jittered randomly. Shape discrimination threshold is measured by two-alternative forced choice and Probit analysis.

We have measured shape discrimination as a function of dot speed and dot contrast for camouflaged dotted rectangles and for uncamouflaged dotted rectangles. Data have been collected through the Summer for two subjects and are now complete. We are now analyzing the data.

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2b. Status of the research effort: neuromagnetism and electrophysiology

(4) *Theoretical and technical work on the two-input technique for characterizing nonlinear processing in sensory pathways*

Neurons that respond asymmetrically – e.g. to leftwards versus rightwards motion, to increase versus decrease of spatial contrast, or to rise versus fall of auditory tone frequency – can be described as rectifiers. In addition to asymmetric response, many neurons perform functionally – important nonlinear processing such as ratio-ing,[11-13] multiplication,[14] or logarithmic compression.

We have developed a theoretical basis and a practical technique for investigating nonlinear processing in sensory pathways. The basic procedure can be traced back at least to Bennet's 1933 paper[15] on radio communication. In general terms, Bennet's basic idea was to stimulate the nonlinearity being studied with two simultaneous inputs, one of temporal frequency F_1 Hz and the other of F_2 Hz. Any other frequency terms *must* be due to nonlinear processing.

Bennet[15] discussed the case of simple linear rectifier, and showed theoretically that the output included many terms of frequency $(nF_1 \pm mF_2)$, where n and m are integral or zero.

Bennet considered the case that the amplitude of the F_1 Hz input is held constant while the amplitude of the F_2 Hz input is progressively increased from zero, and developed a theoretical method for calculating how the amplitudes of the several discrete frequency terms vary with the F_2 Hz input amplitude.

Bennet's theoretical work was further developed by Rice but was not extended previously to rectifiers of any given characteristic nor to cascades of rectifiers.

We have made the following further steps. We have developed a theoretical treatment of the following cases: (a) single compressive rectifier, $y = x^{1/n}$; (b) single accelerating rectifier y =

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x^n; (c) cascaded sequence of rectifiers, e.g. multiple compressive third root rectifiers in series, and mixed cascaded rectifiers, e.g. compressive third root followed by accelerating square law; (d) two parallel rectifiers (compressive or accelerating) converging onto a third (compressive or accelerating); (e) a single rectifier whose characteristic matches the physiological contrast sensitivity characteristics, i.e. a threshold – initial acceleration – subsequent compression.[16]

A sequence of cascaded rectifiers (c above) is intended to model a sequence of rectifier-like neurons as, for example, the photoreceptor–bipolar–ganglion cell–LGN cell–cortical cell sequence. Case (d) above is intended to model the dichoptic visual situation (i.e. signals leaving nonlinear processors in left and right eyes converging onto binocular cortical neurons) or the dichoptic situation (i.e. signals leaving nonlinear processors in left and right ears converging onto binaurally-driven cells).

We went on to compute the amplitudes of several (up to 20) of the discrete nonlinear frequency components as a function of the amplitude of the F_2 Hz input.[16]

In brief, this theoretical work suggests that *the resulting family of curves comprises a "fingerprint" of the type of nonlinearity. Because so many different frequency components are computed, just as with a human "fingerprint," there is high specificity, allowing different kinds of nonlinearity to be recognized.*

The following is an outline of this mathematical work. A full treatment of the work to date has been published in the *Journal of Theoretical Biology*.[17]

A METHOD FOR DERIVING THE RESPONSE OF ASYMMETRIC NONLINEARITIES TO A SUM OF TWO SINEWAVES

We first consider the simple case of a half-wave linear rectifier fed with a single sinewave, and then with the sum of two sinewaves. After this introduction we go on to the accelerating and

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compressive rectifiers fed with the sum of two sinewaves, and finally discuss cascaded rectifiers and parallel-cascaded rectifiers of the same type and of mixed types.

[1] HALF-WAVE LINEAR RECTIFIER : RESPONSE TO A SINGLE SINUSOID.

Let the input to a half-wave rectifier ($y = cx, \quad x \geq 0; \quad y = 0, \quad x < 0$) be $e(t) = A\cos(pt + \theta_p) = A\cos x$, where $p = 2\pi*$frequency of input and $\theta_p =$ phase. Taking $A > 0$ and the constant of proportionality $c = 1$, the output is a function $f(x)$, where

$$f(x) = \begin{cases} A\cos x, & \cos x \geq O \\ 0, & \cos x < 0. \end{cases}$$

We can express $f(x)$ in terms of a Fourier series in x, where

$$f(x) = a_0/2 + \sum_{n=1}^{\infty} a_n \cos nx$$

and

$$\begin{aligned} a_n &= \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} f(x)\cos nx\,dx, \quad f(x) = 0, \ |x| > \pi/2, \ n = 0,1,2,\ldots \\ &= \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} A\cos x \cos nx\,dx \\ &= \frac{A}{\pi}\int_0^{\pi/2} [\cos(n+1)x + \cos(n-1)x]\,dx, \quad n \neq 1 \\ &= \begin{cases} \frac{2A(-1)^{(2+n)/2}}{(n^2-1)\pi} & n \ \ even \\ 0 & n \ \ odd, \ n \neq 1, \end{cases} \end{aligned}$$

and $$a_1 = \frac{2}{\pi}\int_0^{\pi/2} \cos^2 x\,dx = \frac{1}{2}$$

$$\Rightarrow \quad f(x) = \frac{A}{\pi} + \frac{A}{2}\cos x + \frac{2A}{3\pi}\cos 2x - \frac{2A}{15\pi}\cos 4x + \cdots.$$

[2] HALF-WAVE LINEAR RECTIFIER : RESPONSE TO THE SUM OF TWO SINUSOIDS

If the input voltage is given by

$$e(t) = P\cos(pt + \theta_p) + Q\cos(qt + \theta_q)$$

then we can rewrite this as

$$e(t) = P[\cos(pt + \theta_p) + k\cos(qt + \theta_q)]$$

where $k = Q/P$.

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The case $k \leq 1$

Without loss of generality, we can take $P > 0$ and the constant of proportionality, c, to be 1. First let us consider $k \leq 1$, and set

$$f(x,y) = \begin{cases} P(\cos x + k\cos y), & (\cos x + k\cos y) \geq 0 \\ 0, & (\cos x + k\cos y) < 0 \end{cases}$$

where $x = (pt + \theta_p)$, and $y = (qt + \theta_q)$.

$f(x,y)$ is a surface in and above the (x,y)-plane, bounded by $(\cos x + k\cos y) = 0$ in the (x,y)-plane. Clearly adding 2π to x or y leaves $f(x,y)$ unaltered, so $f(x,y)$ is a periodic function in x and y. So if we know $f(x,y)$ in the rectangle $(-\pi,\pi) * (-\pi,\pi)$ we will know all its values.

Since $f(x,y)$ is bounded in the rectangle $(-\pi,\pi) * (-\pi,\pi)$ and its first derivatives are bounded, the double Fourier series in (x,y) of $f(x,y)$is a valid expansion in this rectangle (Hobson, 1926). If the Fourier series of $f(x,y)$is valid in the (x,y) plane, then it is valid on the line $py - qx = p\theta_q - q\theta_p$, found by eliminating t from $x = (pt + \theta_p)$, $y = (qt + \theta_q)$.

The boundaries of $f(x,y)$are the curves given by $\cos x + k\cos y = 0$, as shown by Fig. 1.98. In the shaded area, $\cos x + k\cos y \geq 0$, elsewhere $\cos x + k\cos y < 0$, giving $f(x,y) = 0$. Since $f(x,y)$is an even function, its double Fourier expansion will be a cosine series given by

$$f(x,y) = \frac{1}{2}A_{00} + \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{\pm mn}\cos(mx \pm nx) + A_{10}\cos x + A_{01}\cos y$$

where

$$\begin{aligned} A_{\pm mn} &= \frac{1}{2\pi^2}\int_{-\pi}^{\pi}\int_{-\pi}^{\pi} f(x,y)\cos(mx \pm nx)\,dx\,dy \\ &= \frac{1}{2\pi^2}\int_{-\pi}^{\pi}\int_{-\pi}^{\pi} f(x,y)[\cos mx\cos ny \mp \sin mx\sin ny]dx\,dy. \end{aligned}$$

Since the region is symmetrical in both x and y, $A_{\pm mn}$ can be found by using one quarter of the plane. Hence

$$A_{\pm mn} = \frac{2P}{\pi^2}\int_0^{\pi}\cos ny\int_0^{\arccos(-k\cos y)}(\cos x + k\cos y)\cos mx\,dx\,dy$$

since $f(x,y) = 0$ when $x > \arccos(-k\cos y)$.

The calculation for $A_{\pm mn}$, when $m = 2$ and $n = 0$, is shown below.

$$\begin{aligned} A_{20} &= \frac{2P}{\pi^2}\int_0^{\pi}\int_0^{\arccos(-k\cos y)}(\cos x + k\cos y)\cos 2x\,dx\,dy \\ &= \frac{2P}{2\pi^2}\int_0^{\pi}(1 - k^2\cos^2 y)^{3/2}dy \\ &= \frac{4P}{3\pi^2}\int_0^1\frac{(1-k^2z^2)^{3/2}}{(1-z^2)^{\frac{1}{2}}}dz \\ &= \frac{4P}{3\pi^2}\left\{\int_0^1\left(\frac{1-k^2z^2}{1-z^2}\right)^{\frac{1}{2}}dz - \int_0^1 k^2z^2\left(\frac{1-k^2z^2}{1-z^2}\right)^{\frac{1}{2}}dz\right\}. \end{aligned}$$

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Using the identity

$$\left(\frac{(1-k^2z^2)}{(1-z^2)}\right)^{\frac{1}{2}} = \left\{\frac{1}{\{(1-k^2z^2)(1-z^2)\}^{\frac{1}{2}}} - \frac{k^2z^2}{\{(1-k^2z^2)(1-z^2)\}^{\frac{1}{2}}}\right\}$$

and letting

$$Z_s = \int_0^1 \frac{z^s}{\{(1-z^2)(1-k^2z^2)\}^{\frac{1}{2}}} dz$$

then $Z_0 = K$, the complete elliptic integral of the first kind, and Z_s can be expressed in terms of Z_{s-2} and Z_{s-4} by using the recurrence formula

$$Z_s = \frac{(s-2)(1+k^2)Z_{s-2} - (s-3)Z_{s-4}}{(s-1)k^2}$$

for $s \geq 4$, (Bennett, 1933). From

$$Z_2 = (K-E)/k^2,$$

where E is the complete elliptic integral of the second kind, we have that

$$\begin{aligned} A_{20} &= \frac{4P}{3\pi^2}\left[E - k^2Z_2 + k^4Z_4\right] \\ &= \frac{4P}{3\pi^2}\left[E - (K-E) + (2+k^2)K/3 - 2(1+k^2)E/3\right] \\ &= \frac{4P}{9\pi^2}\left[2(2-k^2)E - (1-k^2)K\right]. \end{aligned}$$

This gives the amplitude of the frequency $(mx \pm ny)/2\pi$ and the phase angle $(m\theta_p \pm n\theta_q)$. The values of the amplitudes for m and $n = 0, 1, 2, 3, 4$ are as follows :

$$\begin{aligned} A_{00} &= \frac{4P}{\pi^2}[2E - (1-k^2)K] \\ A_{10} &= \frac{P}{2} \\ A_{01} &= \frac{kP}{2} \\ A_{20} &= \frac{4P}{9\pi^2}[2(2-k^2)E - (1-k^2)K] \\ A_{11} &= \frac{4P}{3\pi^2 k}[(1+k^2)E - (1-k^2)K] \\ A_{02} &= \frac{4P}{9\pi^2 k^2}[2(2k^2-1)E + (2-3k^2)(1-k^2)K] \\ A_{40} &= \frac{4P}{225\pi^2}[(-38 + 88k^2 - 48k^4)E + (23 - 47k^2 + 24k^4)K] \\ A_{31} &= \frac{4P}{45\pi^2 k}[(8k^4 - 13k^2 + 3)E - (1-k^2)(3-4k^2)K] \\ A_{22} &= \frac{4P}{15\pi^2 k^2}[(k^2-1)(k^2-2)K - 2(k^4 - k^2 + 1)E] \\ A_{13} &= \frac{4P}{45\pi^2 k^3}[(8 - 13k^2 + 3k^4)E - (8 - 17k^2 + 9k^4)K] \\ A_{04} &= \frac{4P}{225\pi^2 k^4}[(k^2-1)(-15k^4 + 64k^2 - 48)K - (38k^4 - 88k^2 + 48)E]. \end{aligned}$$

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The third and higher odd order terms are zero, and

$$K = \int_0^{\pi/2} (1 - k^2 sin^2\theta)^{-\frac{1}{2}} d\theta$$
$$= \int_0^1 [(1 - z^2)(1 - k^2 z^2)]^{-\frac{1}{2}} dz$$

and

$$E = \int_0^{\pi/2} (1 - k^2 sin^2\theta)^{\frac{1}{2}} dz$$
$$= \int_0^1 (1 - k^2 z^2)^{\frac{1}{2}} (1 - z^2)^{-\frac{1}{2}} dz$$

where $k \leq 1$.

The case $k > 1$.

We can rewrite $f(x,y)$ in the following way:

$$f(x,y) = \begin{cases} P(cos\, y + l\, cos\, x)/l, & cos\, y + l\, cos\, x \geq 0 \\ 0, & cos\, y + l\, cos\, x < 0 \end{cases}$$

where $l = 1/k < 1$ and consequently

$$f(x,y) = A'_{00}/2 + \sum_{r=1}^{\infty}\sum_{s=1}^{\infty} A'_{\pm rs} cos(ry \pm sx) + A'_{10} cos\, y + A'_{01} cos\, x$$

where

$$A'_{\pm rs} = \frac{2P}{l\pi^2} \int_0^{\pi} cos\, sx \int_0^{arccos(-l cos x)} (cos\, y + l\, cos\, x) cos\, ry\, dy\, dx.$$

$A'_{\pm rs}$ is the coefficient of $cos(rx \pm sx)$ which may be written as $cos(sx \pm ry)$. So for a given m and n, say M and N, we will have to consider $A_{\pm MN}$, for $k \leq 1$ and $A'_{\pm NM}$ for $k > 1$. For example, let us consider the coefficient of $cos\, 2x$.

$$A'_{\pm 02} = \frac{2P}{l\pi^2} \int_0^{\pi} cos\, 2x \int_0^{arccos(-l cos x)} (cos\, y + l\, cos\, x)\, dy\, dx$$
$$= \frac{4P}{9\pi^2 l^3} [2(2l^2 - 1)E + (2 - 3l^2)(1 - l^2)K]$$
$$= \frac{4Pk^3}{9\pi^2} [2(2/k^2 - 1)E(1/k) + (2 - 3/k^2)(1 - 1/k^2)K(1/k)]$$
$$= \frac{4P}{9\pi^2 k} [2k^2(2 - k^2)E(1/k) + (2k^2 - 3)(k^2 - 1)K(1/k)].$$

Therefore the function of amplitude $g(k)_{\pm mn}$ is given by

$$g(k)_{\pm mn} = \begin{cases} A_{\pm mn}, & k \leq 1 \\ A'_{\pm nm}, & k > 1. \end{cases}$$

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When $k > 1$, we have the following values for $A'_{\pm mn}$ when m and n are $0, 1, 2, 3, 4$:

$$A'_{\pm 00} = \frac{4P}{\pi^2 k}[2k^2 E - (k^2 - 1)K]$$

$$A'_{\pm 10} = \frac{kP}{2}$$

$$A'_{\pm 01} = \frac{P}{2}$$

$$A'_{\pm 20} = \frac{4P}{9\pi^2 k}\left[2(2k^2 - 1)E - (k^2 - 1)K\right]$$

$$A'_{\pm 11} = \frac{4P}{3\pi^2}\left[(k^2 + 1)E - (k^2 - 1)K\right]$$

$$A'_{\pm 02} = \frac{4P}{9\pi^2 k}\left[2k^2(2 - k^2)E + (2k^2 - 3)(k^2 - 1)K\right]$$

$$A'_{\pm 40} = \frac{4P}{225\pi^2 k^3}\left[(23k^4 - 47k^2 + 24)K + (-38k^4 + 88k^2 - 48)E\right]$$

$$A'_{\pm 31} = \frac{4P}{45\pi^2 k^2}\left[(8 - 13k^2 + 3k^4)E - (k^2 - 1)(3k^2 - 4)K\right]$$

$$A'_{\pm 22} = \frac{4P}{15\pi^2 k}\left[(1 - k^2)(1 - 2k^2)K - 2(1 - k^2 + k^4)E\right]$$

$$A'_{\pm 13} = \frac{4P}{45\pi^2}\left[(8k^4 - 13k^2 + 3)E - (8k^4 - 17k^2 + 9)K\right]$$

$$A'_{\pm 04} = \frac{4P}{225\pi^2 k}\left[(1 - k^2)(-15 + 64k^2 - 48k^4)K - k^2(38 - 88k^2 + 48k^4)E\right].$$

The third and higher odd order terms are zero, and E and K are functions of $1/k < 1$.

The function $g(k)_{\pm mn}$is shown for values of k from 0 to 4 in Fig. 1.99. The elliptical integrals were calculated using well-known algorithms (King, 1924. Regan, 1985).

[3] HALF-WAVE SQUARE LAW RECTIFIER : RESPONSE TO THE SUM OF TWO SINUSOIDS.

If the rectifier is of the form $y = cx^2, x \geq 0$ and $y = 0, x < 0$ and if $k \leq 1$ then, as for the half-wave linear rectifier, we can consider the rectifier's output as the function $f(x, y)$ where

$$f(x,y) = \begin{cases} P^2(\cos x + k\cos y)^2, & \cos x + k\cos y \geq 0 \\ 0, & \cos x + k\cos y < 0 \end{cases}$$

where $x = (pt+\theta_p)$, and $y = (qt+\theta_q)$. Again $f(x, y)$ is bounded in the rectangle $(-\pi, \pi) * (-\pi, \pi)$ by $\cos x + k\cos y$ and its Fourier expansion will be a cosine series given by

$$f(x,y) = \frac{1}{2}A_{00} + \sum_{m-1}^{\infty}\sum_{n=1}^{\infty} A_{\pm mn}\cos(mx \pm nx) + A_{10}\cos x + A_{01}\cos y$$

but now

$$A_{\pm mn} = \frac{2P^2}{\pi^2}\int_0^{\pi} \cos ny \int_0^{\arccos(-k\cos y)} (\cos x + k\cos y)^2 \cos mx\, dx\, dy$$

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since $f(x,y) = 0$ when $x > arccos(-k\cos y)$. When $k > 1$, we have

$$A'_{\pm rs} = \frac{2P^2}{l^2\pi^2}\int_0^{\pi} \cos sx \int_0^{arccos(-l\cos x)} (\cos y + l\cos x)^2 \cos ry\, dy\, dx$$
$$= \frac{2P^2k^2}{\pi^2}\int_0^{\pi} \cos sx \int_0^{arccos(-l\cos x)} (\cos y + l\cos x)^2 \cos ry\, dy\, dx$$

where $l = 1/k$. See Fig. 1.100.

[4] HALF-WAVE SQUARE-ROOT RECTIFIER : RESPONSE TO THE SUM OF TWO SINUSOIDS.

Now the rectifier is of the form $y = c\sqrt{x}, x \geq 0$ and $y = 0, x < 0$ and for $k \leq 1$ we will have the function

$$f(x,y) = \begin{cases} P^{\frac{1}{2}}(\cos x + k\cos y)^{\frac{1}{2}}, & \cos x + k\cos y \geq 0 \\ 0, & \cos x + k\cos y < 0 \end{cases}$$

where $x = (pt + \theta_p)$, and $y = (qt + \theta_q)$. Thus

$$A_{\pm mn} = \frac{2P^{\frac{1}{2}}}{\pi^2}\int_0^{\pi} \cos ny \int_0^{arccos(-k\cos y)} (\cos x + k\cos y)^{\frac{1}{2}} \cos mx\, dx\, dy$$

since $f(x,y) = 0$ when $x > arccos(-k\cos y)$ and for $k > 1$, we have

$$A'_{\pm rs} = \frac{2P^{\frac{1}{2}}}{l^{\frac{1}{2}}\pi^2}\int_0^{\pi} \cos sx \int_0^{arccos(-l\cos x)} (\cos y + l\cos x)^{\frac{1}{2}} \cos ry\, dy\, dx$$
$$= \frac{2P^{\frac{1}{2}}k^{\frac{1}{2}}}{\pi^2}\int_0^{\pi} \cos sx \int_0^{arccos(-l\cos x)} (\cos y + l\cos x)^{\frac{1}{2}} \cos ry\, dy\, dx$$

where $l = 1/k$. See Fig. 1.101. Similarly, we can find the response to any half-wave rectifier whose equation is $y = cx^n, x \geq 0; y = 0, x < 0$, where n is any real number.

[5] TWO CASCADED LINEAR HALF-WAVE RECTIFIERS, A.C. COUPLED.

If two rectifiers are D.C. coupled, the output will be the same as a single linear half-wave rectifier. Indeed, if two half-wave rectifiers are D.C. coupled and the first of the series is a linear rectifier, the final output will be the same as that of the second rectifier alone.

After the two sinusoids pass through the first rectifier, their function is given by

$$f(x,y) = \begin{cases} P(\cos x + k\cos y), & (\cos x + k\cos y) \geq 0 \\ 0, & (\cos x + k\cos y) < 0 \end{cases}$$

where $x = (pt + \theta_p)$, and $y = (qt + \theta_q)$. This has a D.C.-level given by $A_{00}/2$, the constant term in the double Fourier series expansion of $f(x,y)$. If our two successive rectifers are linked by A.C. coupling, this D.C.-level must be removed and so the function entering the second rectifier is given by

$$F(x,y) = f(x,y) - A_{00}/2$$

where

$$A_{00} = \frac{2P}{\pi^2}\int_0^{\pi}\int_0^{arccos(-k\cos y)} (\cos x + k\cos y)\, dx\, dy.$$

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After passing through the second rectifier, the output is given by

$$\phi(x,y) = \begin{cases} F(x,y), & F(x,y) \geq 0 \\ 0, & F(x,y) < 0. \end{cases}$$

This can be represented by a double Fourier series where the coefficients $A_{\pm mn}$ are given by

$$A_{\pm mn} = \frac{2P}{\pi^2} \int_0^{\pi} \cos ny \int_0^{\pi} \phi(x,y) \cos mx \, dx \, dy.$$

This is represented graphically in Fig. 1.102.

[6] CASCADED COMPRESSIVE RECTIFIERS

Fig. 1.103 shows the results for two square root ($y = cx^{\frac{1}{2}}, x \geq 0; y = 0, x < 0$) rectifiers in series and Fig. 1.104 shows the results for three square root rectifiers in series.

[7] TWO PARALLEL LINEAR RECTIFIERS WHOSE SUMMED OUTPUTS PASS THROUGH A THIRD LINEAR RECTIFIER : THE DICHOPTIC OR DICHOTIC CASE

In this situation one only frequency ($F1$) passes through rectifier no. 1 and only one frequency ($F2$) passes through rectifier no.2 in parallel with the first rectifier. Then the output from both rectifiers combine to form the input of the third rectifier.

The output of the first rectifier is $f(x)$ where

$$f(x) = \begin{cases} P \cos x, & \cos x \geq 0 \\ 0, & \cos x < 0 \end{cases}$$

with a D.C.-level of P/π. The output of the second rectifier is $g(y)$ where

$$g(y) = \begin{cases} Pk \cos y, & \cos y \geq 0 \\ 0, & \cos y < 0 \end{cases}$$

whose D.C.-level is Pk/π. To adjust for the D.C.-level, the input to the third rectifier will be the function

$$h(x,y) = f(x) - P/\pi + g(y) - Pk/\pi.$$

The output from the third rectifier is given by

$$H(x,y) = \begin{cases} h(x,y), & h(x,y) \geq 0 \\ 0, & h(x,y) < 0. \end{cases}$$

Hence the coefficients of the double Fourier series can be found for

$$A_{\pm mn} = \frac{2P}{\pi^2} \int_0^{\pi} \cos ny \int_0^{\pi} H(x,y) \cos mx \, dx \, dy$$

This rectifier combination is shown in Fig. 1.105 for the case that all three rectifiers have a linear characteristic and coupling is A.C. rather than D.C. Other cases such as mixed rectifiers (e.g. where nos.1 and 2 are cube root rectifiers and no.3 is a square law rectifier) are amenable to the same general mathematical treatment.

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[8] HALF-WAVE RECTIFIER COMBINING ACCELERATING AND COMPRESSIVE SEGMENTS

For this rectifier, the curve equation is given by

$$y = \begin{cases} 0, & x < c \\ d(x-c)^4, & c \le x < 5c \\ (x-c)^{1/16} - g, & 5c \le x \end{cases}$$

where $d = 1/64(4c)^{\frac{63}{16}}$ and $g = \frac{63}{64}(4c)^{\frac{1}{16}}$ and c is chosen suitably. Consequently

$$f(x,y) = \begin{cases} 0, & \cos x + k\cos y < c \\ P^4 d(\cos x + k\cos y - \frac{c}{P})^4, & c \le \cos x + k\cos y < 5c \\ P^{\frac{1}{16}}(\cos x + k\cos y - \frac{c}{P})^{\frac{1}{16}} - g, & 5c \le \cos x + k\cos y \end{cases}$$

where $x = (pt + \theta_p)$, and $y = (qt + \theta_q)$. So

$$A_{\pm mn} = \frac{2}{\pi^2}\int_0^{\pi} \cos ny \int_0^{\pi} f(x,y)\cos mx \, dx \, dy$$

This is shown in Fig. 1.106 with $c = \frac{2\pi}{15}$.

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(5) *Nondestructive zoom-FF*

According to the Heisenberg-Gabor uncertainty principle the limiting frequency resolution of a spectrum, ΔF Hz, is given by

$$\Delta F = 1/\Delta T$$

where ΔT is the recording duration. Thus, for example, a recording of duration 500 sec could, in principle, be analyzed at a resolution of 0.002 Hz so that, if the bandwidth were DC–100 Hz, the spectrum would contain 100 x 500 = 50,000 lines. In practice, however, the FFT usually provides many fewer lines, typically several hundred over a DC–100 Hz bandwidth. We have developed a nondestructive form of zoom FFT that allows high zoom ratios (typically 32 –64) over a wide bandwidth so that we routinely obtain 25,000 or 50,000 lines over DC–100 Hz.

The method is to digitize a time series of duration ΔT by means of a Bruel and Kjaer spectral analyzer. The digitized time series is recorded on floppy disk in an Hewlett-Packard model 9000 computer that controls the analyzer. If, for example, the bandwidth is DC–100 Hz, the sampling rate will be 250 Hz. We routinely digitize a 320-sec duration of the time series. Next, the digitized data are replayed at much increased rate (25 kHz rather than 250 Hz), filtered and, for example, the DC–3.0 Hz section submitted to FFT, giving 800 lines within DC–3.0 Hz. This destroys the time series in the analyzer. Now the time series is replayed again at 25 kHz, heterodyned to shift the 3.0–6.0 Hz segment to DC–3.0 Hz, filtered, resampled, submitted to FFT and shifted back to 3.0–6.0 Hz. This gives us 800 lines within 3.0–6.0 Hz. The process is repeated to give 800 lines in each 3.0 Hz segment between DC and 100 Hz.

The value of this method in electrophysiology is not self-evident. The value is based on our fortunate discovery that the discrete frequency components of the steady-state evoked potential are of ultra-narrow bandwidth, and can be less than 0.002 Hz. Consequently, the noise is spread through 50,000 bins while signal components are concentrated into one or two bins. This gives

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(a) high signal-to-noise ratios, and (b) excellent separation of signal components. The procedure has been published in a book, sponsored in part by AFOSR(18) and is also in press in a journal article.(19)

(6) *Use of the two-sinewave method to measure orientation tuning in human cortical neurons*

A vertical sinewave grating of spatial frequency 5 c/deg was generated on a Joyce CRT and counterphase-modulated at frequency F1 (nominally 8 Hz). A second grating of spatial frequency 5.5 c/deg and variable orientation was generated on a second Joyce CRT and counterphase-modulated at frequency F2 (nominally 7 Hz). The two gratings were optically superimposed. Field size was 10 deg, contrast was 40% for each grating and mean luminance was 250 cd/m^2. Calibration with a linear photocell showed that each CRT was quite linear: second harmonic distortion was below 0.1% of the fundamental component's power. Cross-modulation terms were essentially zero because different CRTs driven by different electronics generated the F1 Hz and F2 Hz gratings. Photocell calibration showed cross-modulation components to be less than 0.01% of the fundamental components' power.

Human steady-state evoked potentials were recorded between electrodes placed on the inion and midway between the inion and the vertex along the midline. Responses were analyzed in the frequency domain by a Bruel and Kjaer analyzer (model 2032) modified to carry out zoom-FFT nondestructively at high zoom factors over a wide bandwidth.(18) Resolution was 0.0078 Hz over a DC–100 Hz bandwidth for a 320-sec recording period, i.e. 12,800 frequency bins were available with frequency-domain averaging also.

The dashed line in Figure 7 plots the amplitude of a (2F1 + 2F2) cross-modulation response term as a function of the orientation difference between the gratings. This cross-modulation term necessarily indicates a nonlinear interaction between visual responses to the fixed vertical grating and the variable-orientation grating, and has previously been shown to be substantially

independent of spatial phase.[20,21] Figure 7 shows that the nonlinear interaction was large when the gratings were parallel and fell to a minimum when their orientations differed by about 30 deg. The half-height full bandwidth of the curve is about 12 deg. The frequency-doubled 2F1 Hz response produced by the fixed vertical grating was suppressed when the two gratings were parallel, but the second grating had comparatively little effect when grating orientations differed by about 30 deg. Similar results were obtained for a second and third subject.

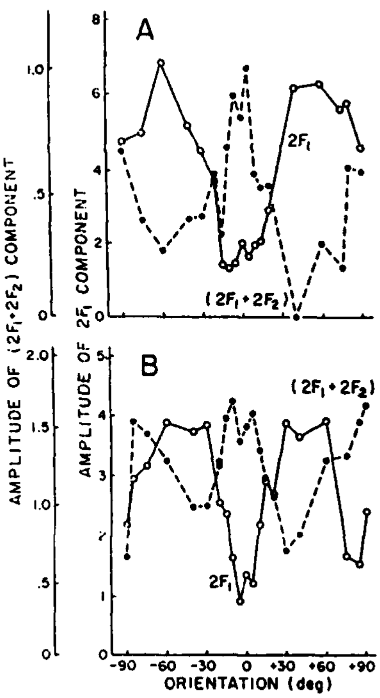

Figure 7. Nonlinear interactions between responses to two gratings as a function of orientation difference. A vertical grating was counterphase-modulated at F1 Hz and a superimposed variable-orientation grating was modulated at F2 Hz. Solid symbols plot the amplitude of the nonlinear cross-modulation (2F1 + 2F2)Hz term in the evoked potential versus the variable grating's orientation. Open symbols plot the frequency-doubled 2F1 Hz term. Results are shown for two subjects.

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The observations reported above can be understood if the (2F1 + 2F2) term is generated by cortical neurons tuned to a narrow range of orientations (such as those described by De Valois *et al.*[22] When the grating orientations differ by more than about 30 deg, most of these neurons cannot encompass both gratings within their orientation bandwidths, and will therefore fail to generate cross-modulation terms.

However, when we placed the two gratings at right angles (the fixed grating remaining vertical), the nonlinear cross-modulation term rose to a second maximum. For subject B this (2F1 + 2F2) term was as large for near-orthogonal gratings as for parallel gratings, and only a little less for subject A. The interaction term was largest at exactly 90 deg orientation difference for subject A but, curiously, peaked sharply just 5 deg from 90 deg for subject B.

This finding that there is a strong nonlinear interaction between responses to vertical and near-horizontal gratings can be understood if we assume that cortical neurons tuned to a narrow range of orientations around the vertical interact nonlinearly with cortical neurons tuned to a narrow range of orientations around the horizontal. It may be relevant that cortical neurons tuned to different orientations can inhibit each other when excited simultaneously.[23,24]

If our findings can be generalized to other kinds of two-dimensional pattern, this would imply that human VEPs to patterns modulated in two dimensions cannot entirely be explained in terms of VEPs to gratings. In particular, the findings reported here could not result from the stimulation of independent, linear, orientation-selective mechanisms.

(7) *Installation of the BTi 7-channel Neuromagnetometer and magnetically shielded room*

Installation of the magnetically shielded room started on September 12, 1988 in a room set aside for the purpose in the Farquarson Building at York University. Installation was completed on schedule. Installation of the neuromagnetometer was started on October 5, 1988. The system dewar was cooled to liquid helium temperature during the week of November 7, and has been

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maintained at liquid helium temperatures since then. Several of the students, technicians and faculty at York have been trained to transfer liquid helium from a 100-litre reservoir to the system dewar. This must be done three times a week. The total expenditure of liquid helium is stabilizing at about 100 litres per two weeks. BTi representatives continued to install and check out the magnetometer up to November 11, and throughout the week of November 14–18, five of us were instructed by BTi representatives on the use of the computer system and recording procedures. During the week of November 21-25, BTi will make final hardware adjustments to the magnetometer. During the first two weeks of December the computers will be shut down while York University Physical Plant Dept. constructs an office within the magnetometer room and installs shelving, benches etc. (This could not be done until now because BTi required extensive floor space to install the shielded room.)

When this work is completed we will be in a position to collect data.

(8) *Book: "Human Brain Electrophysiology: Evoked potentials and evoked magnetic fields in science and medicine" by D. Regan*

Published by Elsevier 1989. This is a single-author book whose writing was sponsored in part by AFOSR. 820 pp, 372 figures.

This book attempts to link (1) our knowledge of evoked electrical and magnetic responses of the human brain to (2) sensory perception and cognition and (3) the properties of single neurons in primate brain. It covers vision, hearing, somatosensation and cognition. There are three parts: technical and mathematical aspects of recording techniques, basic research, and clinical applications.

(9) *Editor of two books: "Binocular Vision" and "Spatial Form Vision"*

Macmillan is producing a series of about 14 volumes under the general title "Vision and Visual Abnormalities." I was invited to edit two of these books. My aim was to choose authors

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who had at least played an important innovative role in the development of their topic over the last 10-20 years and, preferentially, initiated major advances in their topic. In this way I hoped that authors would produce unique insights into how modern understanding of the topics really did emerge so as to provide students with a first-hand understanding of creative science that is often lacking in second-hand accounts. The authors were asked to review their topics at the level of a senior researcher while making the chapter accessible to graduate students. The teaching aspect was emphasized.

I was fortunate that almost all of my first choice authors agreed to contribute, and only very few topics had to be omitted. All except three chapters have now been delivered, and the quality is very high indeed, several chapters being exceptionally interesting. I am confident that the books will be of considerable use to the psychophysics, human factors and single-unit research communities.

MACMILLAN VOL. 10A "BINOCULAR VISION"

H. Collewijn, "Binocular Fusion and Stereopsis with a Moving Head".
J.M. Foley, "Binocular Space Perception".
R. Fox, "Binocular Rivalry".
R. Held, "Development of Binocularity and Stereopsis."
A.E. Kertesz, "Cyclofusion".
H. Ono, "Binocular Single Vision and Binocular Direction".
G. Poggio, "Physiological Basis of Binocular Vision and Stereopsis."
D. Regan, "The Perception of Movement in Depth".
R.D. Reinecke and M.G. Fendick, "Binocular Vision after Strabismus Surgery".
C. Schor, "Abnormalities of Binocular Vision".
C.W. Tyler, "Panum's Fusional Area and the Horopter".
C.W. Tyler, "Cyclopean Vision".

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MACMILLAN VOL. 10B "SPATIAL FORM VISION'

J. Bergen, "Texture and Textons".
I. Bodis-Wollner and D. Regan, "Spatial Vision in Parkinson's Disease".
D. Levy, "Spatial Vision in Amblyopia".
M. Morgan, "Hyperacuities in Spatial Vision".
G. Plant, "Temporal Properties of Spatial Vision".
D. Regan, "Spatial Vision in Multiple Sclerosis".
D. Regan, "Methodology of Contrast Sensitivity Tests in Basic Research and in the Clinic".
J. Rovamo, "The Effects of Eccentricity on Spatial Vision".
K. Ruddock, "Spatial Vision after Cortical Lesions".
R. Sekuler, "Spatial Vision in the Aging Eye".
R. Shapley, "The Physiological Basis of Contrast Sensitivity".
J. van Hof-van Duin and G. Mohn, "Development of Spatial Vision".
H. Wilson, "Psychophysical Models of Spatial Vision and Spatial Hyperacuities".

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